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MARCH 1962

CONICAL FLOW PARAMETERS FOR AIR AND NITROGEN IN VIBRATIONAL EQUILIBRIUM

Paul D. Kelly

Department of the Army Project No. 503-03-001
Ordnance Management Structure Code No. 5010.11.814

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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ABSTRACT

The Taylor-Maccoll equation for supersonic flow about cones has been integrated numerically for air and nitrogen in instantaneous vibrational equilibrium (chemical reactions are assumed to be frozen). Free stream Mach numbers from 8 to 20 were used for 300 °K free stream temperature.

The values of the flow quantities (i.e. velocity components, polar angle, temperature, pressure and density) are given through the shock layer for different values of M_∞ and flow deflection angle at the shock.

It was found that by non-dimensionalizing some of the flow quantities (temperature, pressure and density) with respect to the changes in their values across the shock layer and by plotting them as functions of the non-dimensional shock layer thickness, that the points for different values of M_∞ and cone angle lie along the same curves. This gives an approximate method of obtaining other solutions.

The results presented here are shown to lie between those of Kopal (translation and rotational degrees of freedom only) and Romig (dissociation and ionization included) as is expected.

T A B L E   O F   C O N T E N T S

LIST OF SYMBOLS

Latin

a	=	speed of sound
C_p	=	specific heat at constant pressure
C_v	=	specific heat at constant volume
E_{vib}	=	vibrational energy
M	=	Mach number
p	=	static pressure
q	=	total stream velocity
r	=	radial distance from cone apex
R	=	gas constant per unit mass
T	=	static temperature
u	=	radial velocity component
v	=	velocity component normal to r

Greek

β	=	angular distance from cone axis
γ	=	ratio of specific heats
$\overline{\theta}_v$	=	characteristic vibrational temperature of gas, $^\circ$K
θ_{vib}	$\equiv$	$\overline{\theta}_v / T_\infty$, non-dimensional characteristic vibrational temperature of gas
θ_w	=	flow deflection angle at shock wave
ξ	=	function defined by equation 24
ρ	=	mass density
ψ	=	function defined by equation 25

LIST OF SYMBOLS (Continued)

<u>Subscript</u>

c	=	cone surface
f	=	translational and rotational degrees of freedom only
s	=	constant entropy
w	=	immediately behind the shock wave
∞	=	free stream

<u>Special</u>

Quantities with bars over them have dimensions.

INTRODUCTION

One of the well-known problems of gasdynamics is that of describing the flow field surrounding a cone moving at supersonic speeds in a gas. In their most general form, the conservation equations (i.e., mass, momentum and energy) governing this problem are functions of three independent geometric variables. These variables define a polar spherical coordinate system (See Figure 1) which is appropriate to the cone geometry. If it is assumed that: 1) the cone axis is aligned with the free stream velocity direction; 2) the flow properties are constant along rays originating at the cone apex and 3) the flow field is isentropic throughout, then these conservation equations become functions of one geometric variable (namely, the polar angle measured from the cone axis) only. Furthermore, they may be combined to form a single second-order ordinary differential equation whose solution yields the velocity components as functions of the polar angle. This simplified flow field, called conical flow, was first considered by Taylor and Maccoll[1].*

Extensive tables of conical flow data are given by Kopal[2]. In these tables, it is assumed that the medium behaves as a perfect gas with the ratio of specific heats $\gamma = 1.405$.

*Superscript numbers indicate references at the end of the paper.

Data for conical flow in air at high temperature are given by Romig[3]. In these results effects of vibrational degrees of freedom and chemical reactions between the components of air were incorporated. The assumption of constant entropy implies that thermal and chemical equilibrium must exist. Some approximate results were also given by Zienkiewicz[4].

In this report the equations are set up for a diatomic gas where the vibrational degrees of freedom only are incorporated. Results are given for pure N_2 and also for air using the approximation for specific heat variation given in Reference 5.

CONICAL FLOW OF VIBRATIONALLY EXCITED GASES

1. Thermodynamics of Gases Studied:

It is assumed that the medium is a pure diatomic gas whose molecules vibrate with a quantized simple harmonic motion. It is further assumed that the mechanical (i.e., translational, rotational and vibrational) degrees of freedom are in thermal equilibrium with each other at all times and that chemical reactions do not take place among the gas molecules.

2. Conical Flow Conservation Equations:

The conservation equations (i.e., mass, momentum and energy) describing the flow of a gas around a cone are written with reference to a polar spherical coordinate system (see Fig. 1). Consider cases where the free stream flow direction is aligned with the cone axis. The problem is thereby reduced to an axisymmetric one with r, the linear distance from the cone apex, and β, the angular distance from the cone axis, as the independent variables. If it is further assumed that: 1) the flow properties are constants along rays originating at the cone apex; and 2) that the flow field is isentropic (and hence, inviscid) throughout, then the conservation equations become ordinary non-linear differential equations with β as the independent variable. The flow field is then said to be conical. In order for the flow properties to be constant along rays when the gas molecules possess various mechanical degrees of freedom it is necessary to assume that these various degrees

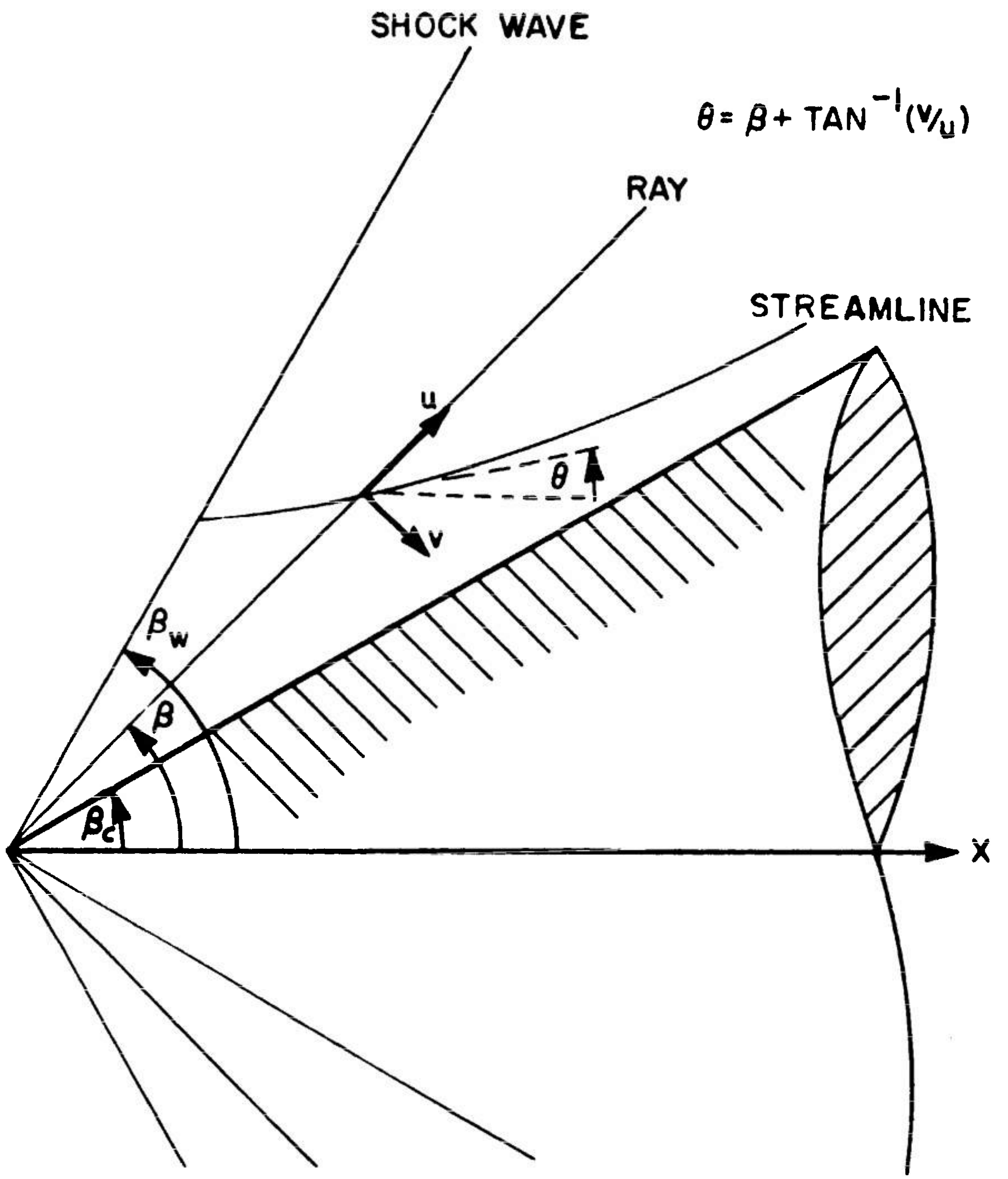

FIG. 1. GEOMETRY OF CONICAL FLOW PROBLEM

of freedom are in thermal equilibrium with each other at all times.

Under these assumptions the conical flow equations for the conservation of mass and momentum for a pure diatomic gas may be written as:

Conservation of mass

$$\frac{d}{d\beta}(\bar{\rho}\,\bar{v}\sin\beta) + 2\,\bar{\rho}\,\bar{u}\sin\beta = 0 \quad , \tag{1}$$

Conservation of momentum in β and $\bar{r}$ directions, respectively

$$\bar{v}\,\frac{d\bar{v}}{d\beta} + \bar{u}\,\bar{v} + \frac{1}{\bar{\rho}}\,\frac{d\bar{p}}{d\beta} = 0 \quad , \tag{2}$$

$$\frac{d\bar{u}}{d\beta} = \bar{v} \quad , \tag{3}$$

where the barred quantities have dimensions. The speed of sound is defined by

$$\bar{a}^2 = (\partial\bar{p} \,/\, \partial\bar{\rho})_s \quad , \tag{4}$$

where the subscript s indicates differentiation at constant entropy. Equations 1, 2, and 4 may be combined to give the Taylor-Maccoll equation.

$$\frac{d^2\bar{u}}{d\beta^2} + \bar{u} = -\,\frac{\bar{u} + \bar{v}\cot\beta}{1 - (\bar{v}/\bar{a})^2} \quad , \tag{5}$$

If $\bar{a}$ were known as a function of $\bar{u}$ and $\bar{v}$, then equations 3 and 5 could be solved for $\bar{u}$ and $\bar{v}$. To find $\bar{a}$, it is necessary to obtain $\bar{q}^2 (= \bar{u}^2 + \bar{v}^2)$ as a function of $\bar{T}$ from the energy equation:

$$C_{pf}\,\bar{T} + \bar{E}_{VIB}\,(\bar{T}) + \frac{\bar{q}^2}{2} = C_{pf}\,\bar{T}_\infty + \frac{\bar{q}_\infty^2}{2} \qquad , \tag{6}$$

where the subscript f means that the gas molecules possess only translational and rotational degrees of freedom. The term $\bar{E}_{VIB}\,(\bar{T})$ is the vibrational energy of the molecules. It is assumed that the vibrational energy is negligible in the free stream. With the assumption of quantized simple harmonic oscillators the vibrational energy term may be written as

$$\bar{E}_{VIB}\,(\bar{T}) = \frac{R\ \bar{\theta}_v}{e^{\bar{\theta}_v/\bar{T}} - 1} \qquad , \tag{7}$$

where $\bar{\theta}_v$ is the characteristic vibrational temperature of the gas. For the gases considered here the speed of sound may be written as a function of $\bar{T}$, and hence of $\bar{q}^2$ $(= \bar{u}^2 + \bar{v}^2)$, as follows:

$$\bar{a}^2 = \left\{\frac{C_{pf}/R + C_{VIB}\ (\bar{T})\ /\ R}{C_{vf}/R + C_{VIB}\ (\bar{T})\ /\ R}\right\} R\,\bar{T} \qquad , \tag{8}$$

where

$$\frac{C_{VIB}\ (\bar{T})}{R} = \frac{1}{R}\,\frac{d\,\bar{E}_{VIB}}{d\,\bar{T}} = \left[\frac{\bar{\theta}_v\ /\ 2\bar{T}}{\sinh\ (\bar{\theta}_v\ /\ 2\bar{T})}\right]^2 . \tag{9}$$

A simultaneous solution of equations 3, 5, 6, 7, 8, and 9 yields $\bar{u}$, $\bar{v}$ and $\bar{T}$ as functions of β.

The pressure and density may then be found as functions of β by solving equation 2 and the equation of state of the gas, which is given as:

$$\bar{p} = \bar{\rho} R \bar{T} \qquad . \tag{10}$$

For convenience introduce the following non-dimensional variables: $u \equiv \bar{u} / \bar{q}_\infty$; $v \equiv \bar{v} / \bar{q}_\infty$; $q \equiv \bar{q} / \bar{q}_\infty$; $a \equiv \bar{a} / \bar{q}_\infty$; $T \equiv \bar{T} / \bar{T}_\infty$; $p \equiv \bar{p} / \bar{p}_\infty$; $\rho \equiv \bar{\rho} / \bar{\rho}_\infty$; $E_{VIB}(T) \equiv \bar{E}_{VIB}(\bar{T}) / C_{pf}\bar{T}_\infty$ and $\theta_{VIB} \equiv \bar{\theta}_V / \bar{T}_\infty$. These lead to the following new set of equations:

$$\frac{dp}{d\beta} = -\gamma_f M_\infty^2 \frac{p\,v}{T} \left[\frac{dv}{d\beta} + u\right] \tag{11}$$

$$\frac{du}{d\beta} = v \tag{12}$$

$$\frac{d^2u}{d\beta^2} + u = -\frac{u + v \cot\beta}{1 - (v/a)^2} \tag{13}$$

$$T + E_{VIB}(T) + \left(\frac{\gamma_f - 1}{2}\right) M_\infty^2 q^2 = 1 + \left(\frac{\gamma_f - 1}{2}\right) M_\infty^2 \tag{14}$$

$$E_{VIB}(T) = \frac{R\,\theta_{VIB}}{C_{pf}} \frac{1}{(e^{\theta_{VIB}/T} - 1)} \tag{15}$$

$$a^2 = \left[\frac{C_{pf} / R + C_{VIB}(T)/R}{C_{vf} / R + C_{VIB}(T)/R}\right] \frac{T}{\gamma_f M_\infty^2} \qquad (16)$$

$$\frac{C_{VIB}(T)}{R} = \left[\frac{\theta_{VIB} / 2T}{\sinh(\theta_{VIB}/2T)}\right]^2 \qquad (17)$$

and

$$p = \rho T \qquad (18)$$

A solution of equations 11 - 18 with the appropriate initial conditions, which will be given in a later section, is sufficient to describe the conical flow field completely.

3. Method of Solution:

Since the flow variables can easily be found on a conical shock wave, it is convenient from a computational standpoint to specify the shock wave angle and integrate equations 11-18 from the shock wave to the body. By using this method of solving the equations integral values for the free stream Mach number and shock wave angle may be used, but the cone angles are determined by the solution and are not known beforehand.

When starting at the shock and integrating towards the body the terminal boundary condition is the vanishing of the v component of velocity (i.e., v = 0) on the cone. In order to make it easy for the digital computer to decide when v is zero the independent variable is chosen to be v rather

than β. Also for ease of computation the differential form of the energy equation (equation 14) is used. By incorporating these simplifications* into equations 11 - 18, the final form of these equations is:

$$\frac{dp}{dv} = -\gamma_f M_\infty^2 \left[\frac{p\,v}{T}\right]\left[u \frac{d\beta}{dv} + 1\right] \tag{19}$$

$$\frac{du}{dv} = -v\,\xi \tag{20}$$

$$\frac{d\beta}{dv} = -\xi \tag{21}$$

$$\frac{dT}{dv} = -\frac{(\gamma_f - 1)\, M_\infty^2\, v\,(1 - u\,\xi)}{(1 + \psi)} \tag{22}$$

$$\rho = p/T \tag{23}$$

where

$$\xi \equiv \frac{1}{u + \dfrac{u + v \cot\beta}{1 - \gamma_f M_\infty^2 \dfrac{v^2}{T}\left(\dfrac{1/\gamma_f + \psi}{1 + \psi}\right)}} \tag{24}$$

$$\psi \equiv \frac{\gamma_f - 1}{\gamma_f}\left[\frac{\theta_{VIB}/2T}{\sinh(\theta_{VIB}/2T)}\right]^2 \tag{25}$$

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*These simplifications were suggested by Mr. R. Makino.

and

$$\gamma_f \equiv C_{pf} / C_{vf}$$

This set of equations (19 - 25) has been programmed for the BRL ORDVAC digital computer. If the machine is given M_∞, γ_f, θ_{VIB} (initial constants) and v_W, u_W, β_W, T_W, p_W (values of flow quantities immediately behind the shock wave), it computes v, u, β, T, p and ρ through the conical shock layer and stops on the cone surface when v equals zero.

4. Oblique Shock Equations - Initial Conditions for Conical Flow Equations:

The initial conditions which are necessary to solve equations 19 - 25 are the flow quantities just behind the conical shock wave attached to the cone. To obtain these initial conditions the oblique shock equations for a pure diatomic gas in thermal equilibrium (whose molecules have their vibrational degrees of freedom excited) must be solved.

In non-dimensional form, these equations are[5] :

$$q_W^2 = \frac{2}{\gamma_f M_\infty^2}\left[\frac{\gamma_f M_\infty^2}{2} - \left(\frac{\gamma_f}{\gamma_f - 1}\right)(T_W - 1) + \theta_{VIB}\left(\frac{1}{e^{\theta_{VIB}} - 1} - \frac{1}{e^{\theta_{VIB}/T_W} - 1}\right)\right] , \qquad (26)$$

$$p_w = 2\left\{\left(1 + \gamma_f M_\infty^2 \frac{q_w^2}{T_w}\right) - \frac{1}{T_w}\left(1 + \gamma_f M_\infty^2\right) + \right.$$

$$\left. + \sqrt{\left[\left(1 + \gamma_f M_\infty^2 \frac{q_w^2}{T_w}\right) - \frac{1}{T_w}\left(1 + \gamma_f M_\infty^2\right)\right]^2 + \frac{4}{T_w}}\right\}^{-1}, \qquad (27)$$

$$\sin^2 \beta_w = \frac{q_w^2 - 1}{(T_w/p_w)^2 - 1}, \qquad (28)$$

$$\sin^2 \theta_w = \frac{1 - \sin^2 \beta_w}{1 - \sin^2 \beta_w \left[1 - \left(\frac{\gamma_f M_\infty^2}{p_w - 1} - 1\right)^2\right]}, \qquad (29)$$

$$u_w = q_w \cos\left(\beta_w - \theta_w\right), \qquad (30)$$

$$v_w = - q_w \sin\left(\beta_w - \theta_w\right), \qquad (31)$$

where θ is the flow deflection angle and the subscript w indicates quantities immediately behind the shock wave.

Equations 26 - 31 have been programmed* for the ORDVAC. If the machine is given M_∞, γ_f, θ_{VIB} and θ_w, it will compute v_w, u_w, β_w, T_w, and p_w, using an iterative method. These are the initial conditions for the set of equations 19 - 25.

*This program was initiated by Mr. J. South.

The computer program which solves the oblique shock equations (26 - 31) has been combined with the one which solves the conical shock layer equations (19 - 25), so that if the machine is given M_∞, γ_f, θ_{VIB}, and θ_W it will solve the conical flow problem completely.

5. <u>Numerical Solution of Complete Conical Flow Problem</u>:

The computer program which solves equations 19 - 31 has been run for a number of cases, i.e., combinations of the parameters M_∞ and θ_W. Two pure diatomic gases have been considered here. The first is air, using the approximation of Reference 5. Accordingly, air is approximated by a fictitious diatomic gas whose characteristic vibrational temperature is a mass weighted average of the characteristic vibrational temperatures of O_2 and N_2. The second gas considered is pure nitrogen. For all cases considered $\gamma_f = 1.40$.

The following table shows the range of parameters covered and indicates the cases (marked by X) which have been computed.

M_∞ \ θ_W	10°	20°	30°	35°	40°	41°	44°
8	.	.	X	X	X	—	X
10	X	X	X	X	X	—	X
12	X	X	X	X	X	—	X
14	X	X	X	X	X	X	
16	X	X	X	X			
18	X	X	X				
20	X	X					

(The cases marked by dots were omitted because they differed inappreciably from frozen Taylor-Maccoll Flow.)

RESULTS

1. <u>Presentation of Results:</u>

The results of solving equations 19 - 31 are presented in numerical form in Tables I and II for air and N_2, respectively. The calculations are grouped according to increasing M_∞; for each M_∞ the cases are given in order of decreasing cone angle. The variables which are solved for are: v, u, β, T, p and ρ. The first line of each case is the set of flow quantities just behind the conical shock wave; the last line is the set of flow quantities on the cone surface. The lines lying between these two are the flow quantities for equal increments in v.* The results of the numerical integration are presented to six figures. This solution is accurate to at least four significant figures. When the cone surface pressures for the air computations are plotted against $M_\infty \sin \beta_c$, the "hypersonic similarity parameter" used by Romig[3], all the points lie essentially on one smooth curve. This result occurs also for surface temperatures and densities. In addition, for all the nitrogen cases these flow variables exhibit the same surface behavior, and the curves obtained are practically identical with those for air. Plots of surface pressure, temperature, and density are given in Fig. 2.

The "similarity" behavior is also found at the shock wave in that certain variables can be plotted as functions of $M_\infty \sin \beta_c$ alone.

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*The integration was carried out in thirty steps, but only every fifth one was printed.

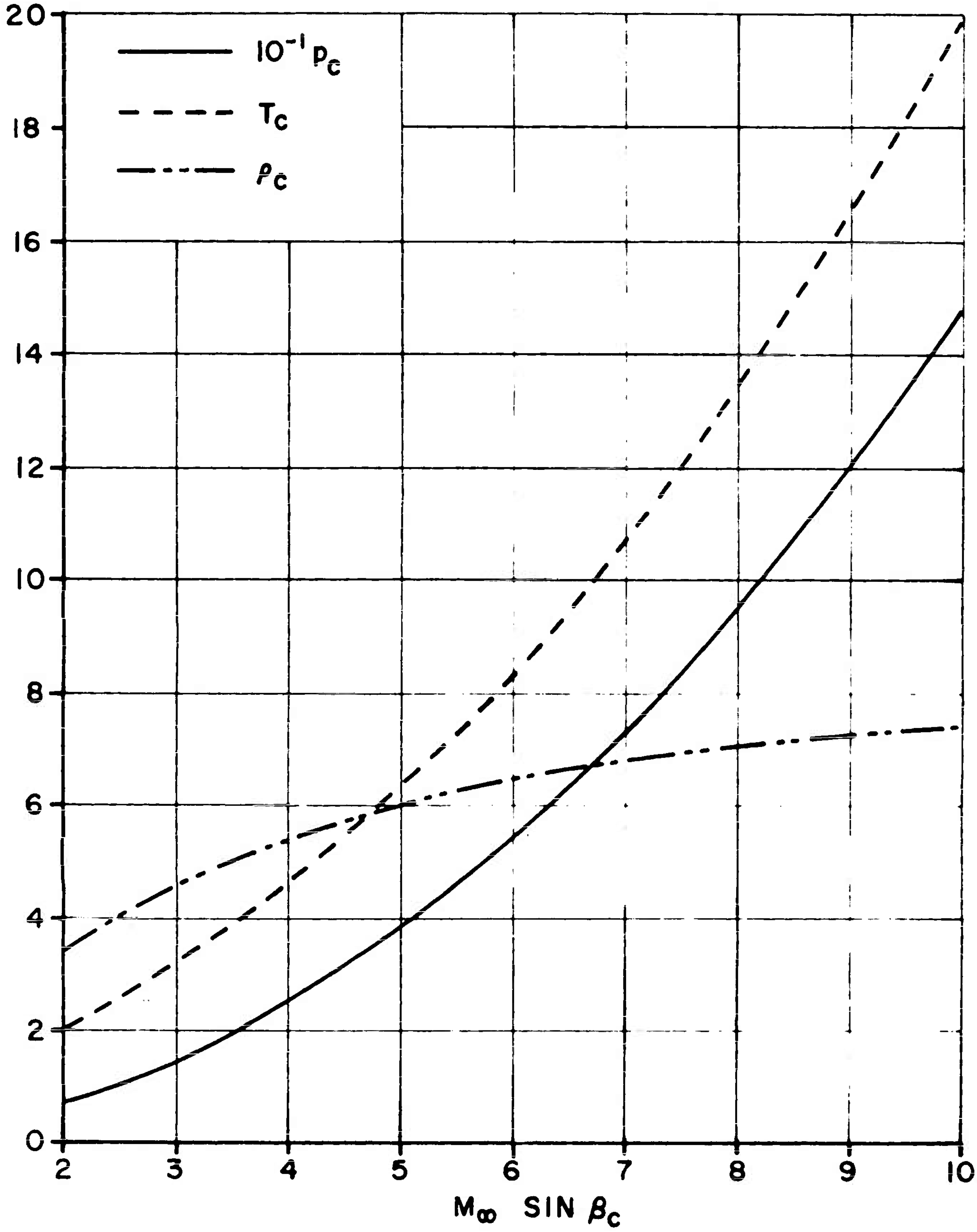

FIG. 2. CONE SURFACE PRESSURE, TEMPERATURE, AND DENSITY Vs. M_∞ SIN β_c FOR AIR AND NITROGEN.

Fig. 3 gives curves for $M_\infty \sin \beta_w$, p_w, and T_w; again the curves for nitrogen and air are nearly coincident.

2. Discussion of Results:

In plotting the results against a non-dimensional shock layer thickness (i. e., $[\beta - \beta_c] / [\beta_w - \beta_c]$) it was noticed that the profiles of variation of flow variables were similar for different cases (i. e., different values of M_∞ and β_c). Pressure, temperature, and density were then non-dimensionalized with respect to their changes in value across the shock layer (e. g., $[p - p_c] / [p_w - p_c]$) and plotted against $(\beta - \beta_c)/(\beta_w - \beta_c)$. It was found that the points from all the cases lay along one smooth curve for each flow variable. Furthermore, the three curves for p, T, and ρ were practically identical (both for air and nitrogen). The "universal" curve for these three quantities is shown in Fig. 4.

As a result of the similarity phenomena exhibited above one can determine p, T, and ρ (to about two digit accuracy) over the entire vibrational equilibrium conical flow field for any given case in a wide range of M_∞ and β_c by using Figs. 2, 3, and 4. One must be certain beforehand that a conical flow exists, however. To the accuracy of the graphs the results for air and nitrogen are the same.

Tables I and II have another possible application, in that the values of the flow variables at the shock wave can furnish initial data for calculation of non-equilibrium flows with dissociation.

3. Comparison with Other Work:

In Figs. 5 and 6 the cone surface temperature and density, respectively, are compared with those obtained by Kopal[2] (translational

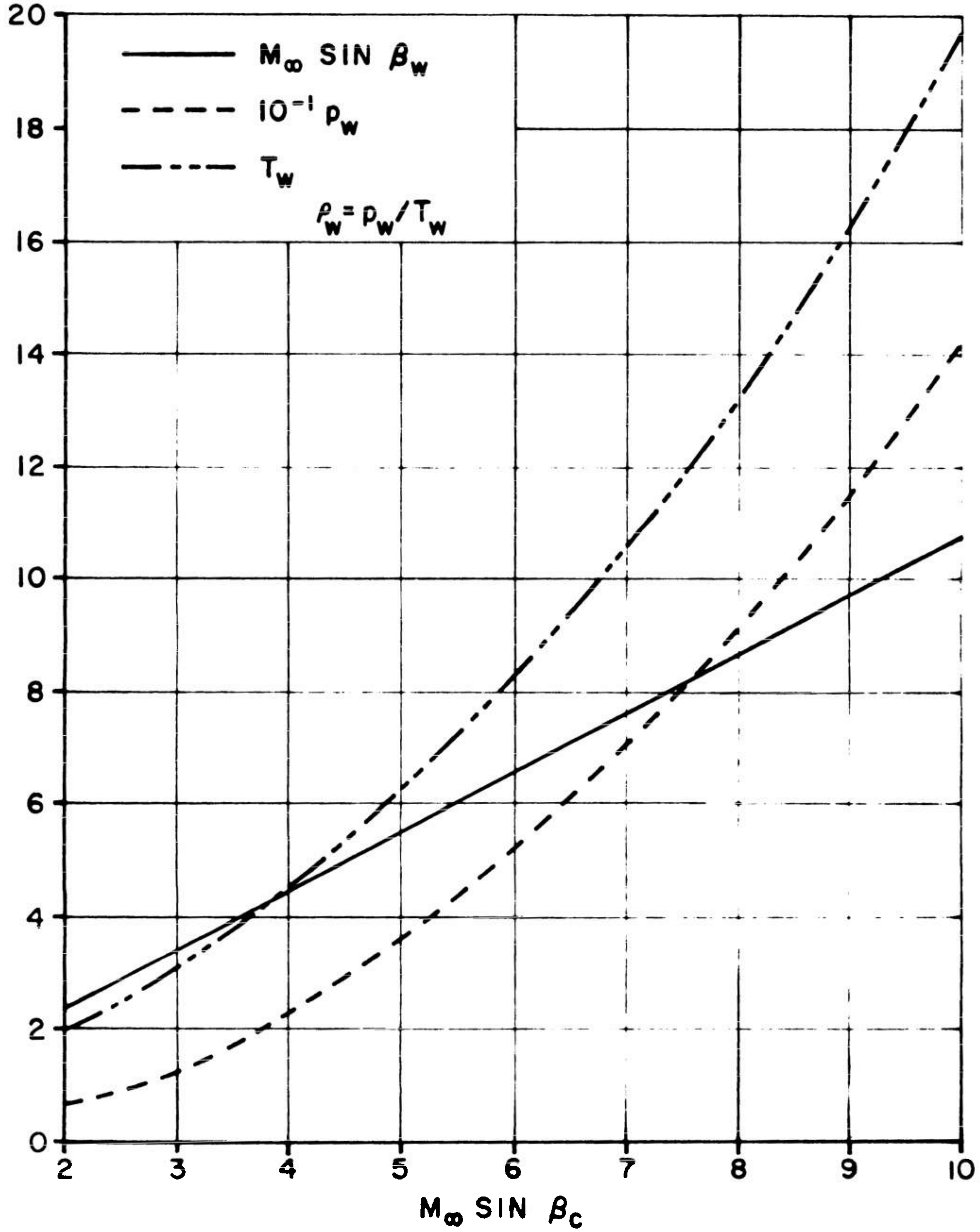

FIG. 3. SHOCK WAVE ANGLE, PRESSURE, AND TEMPERATURE Vs. M_∞ SIN β_c FOR AIR AND NITROGEN.

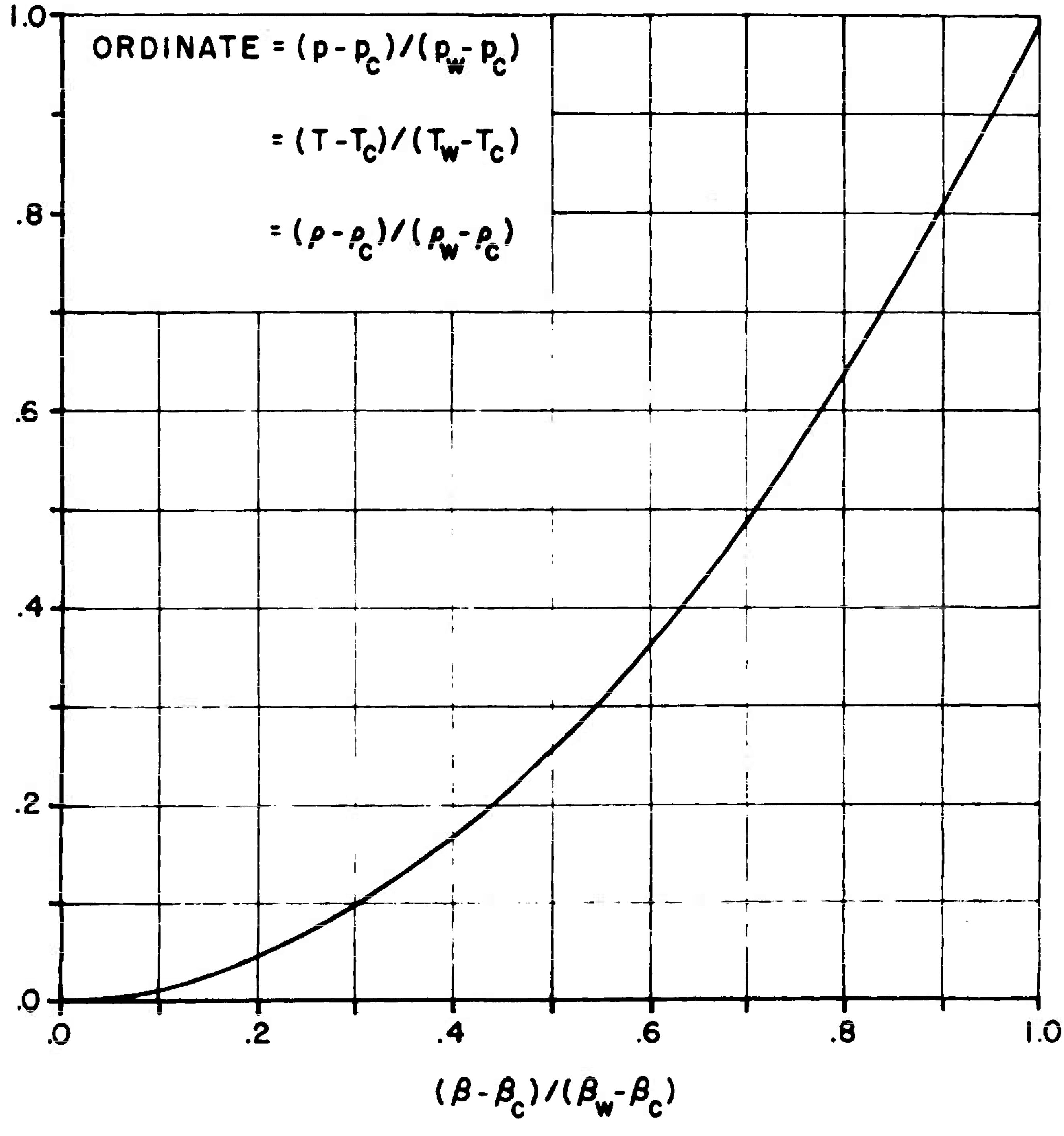

FIG. 4. VARIATION OF PRESSURE, TEMPERATURE, AND DENSITY ACROSS THE SHOCK LAYER FOR AIR AND NITROGEN.

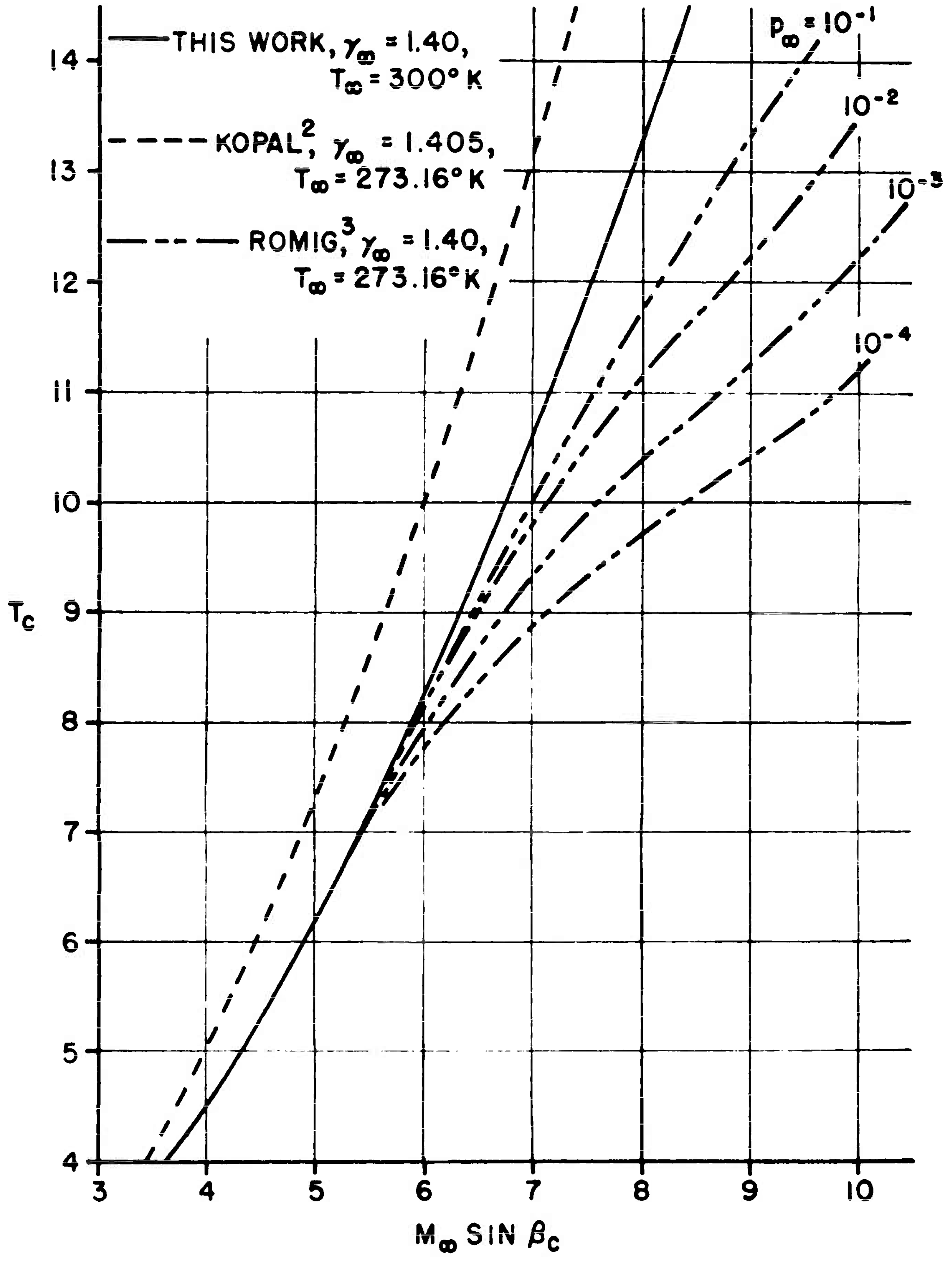

FIG. 5. CONE SURFACE TEMPERATURE

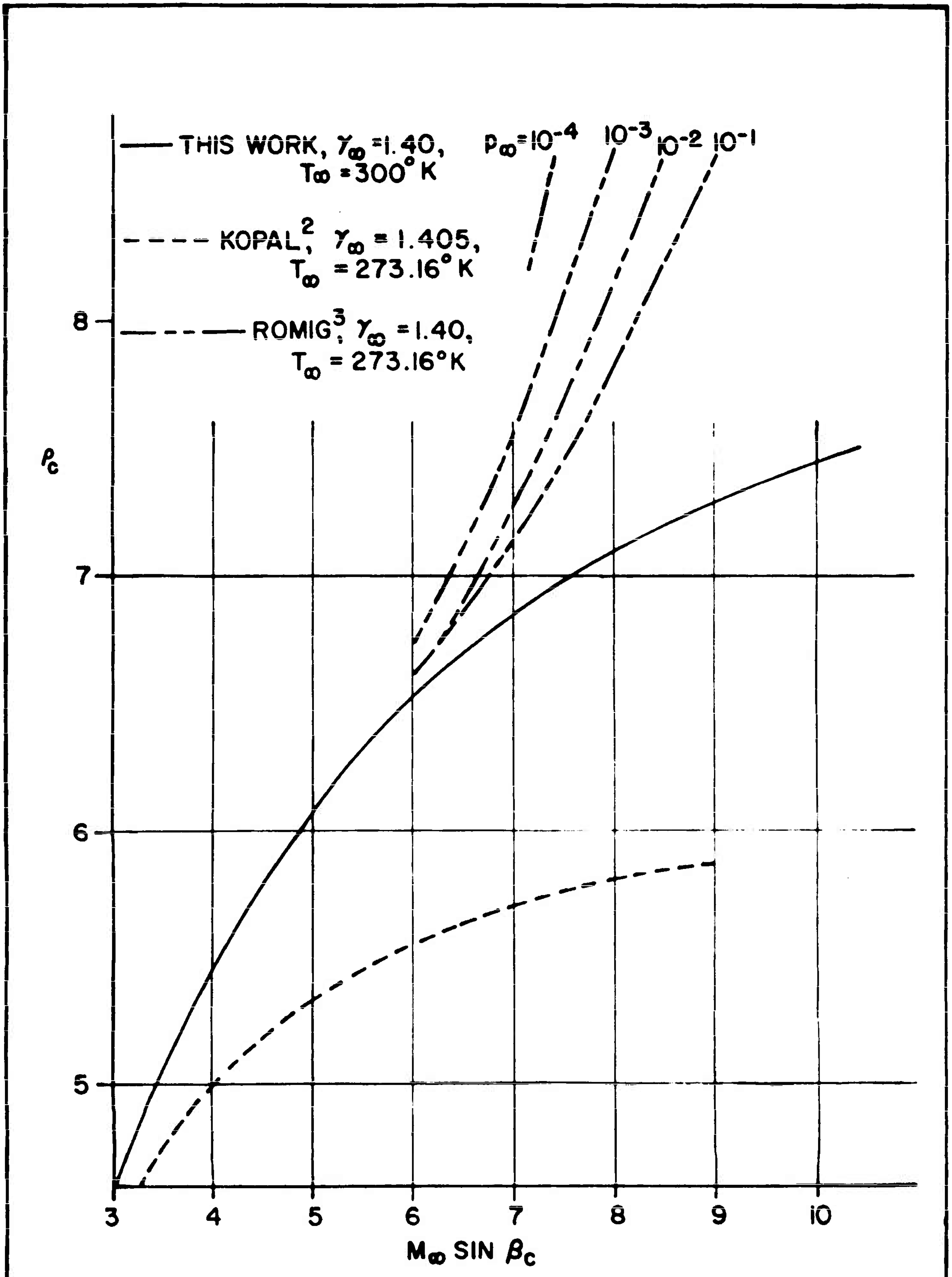

FIG. 6. CONE SURFACE DENSITY

and rotational degrees of freedom only) and Romig[3] (dissociation and ionization included) by plotting them all against the parameter $M_\infty \sin \beta_c$. The results presented here are seen to lie between those presented by Kopal and Romig; this is an expected result.

ACKNOWLEDGMENTS

The author wishes to express sincere appreciation to Dr. R. Sedney for his help and guidance throughout the writing of this report. He also would like to thank Mr. P. Schlegel and Mrs. G. Beck for programming and performing the calculations on the ORDVAC, and Mr. N. Gerber for preparing the manuscript for publication.

PAUL D. KELLY

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VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE I AIR

$\overline{T}_\infty$ = 300°K, γ_∞ = 1.4, $\overline{\theta}_v$ = 3101.6°K

M_∞ = 8.0000000 θ_w = 44° β_c = 50.88°

v	u	β°	T	p	ρ
-.133366	.526889	58.2043	8.71942	55.5696	6.3730
-.111138	.529503	56.9794	8.74670	56.3372	6.4409
-.088910	.531651	55.7486	8.76880	56.9651	6.4963
-.066683	.533322	54.5182	8.78593	57.4554	6.5394
-.044455	.534510	53.2935	8.79819	57.8083	6.5704
-.022227	.535217	52.0795	8.80559	58.0223	6.5892
-.000000	.535450	50.8810	8.80809	58.0946	6.5955

M_∞ = 8.0000000 θ_w = 40° β_c = 45.60°

v	u	β°	T	p	ρ
-.126794	.622286	51.5167	7.61461	47.0101	6.1736
-.105662	.624288	50.5296	7.63944	47.6822	6.2415
-.084529	.625936	49.5366	7.65956	48.2324	6.2970
-.063397	.627219	48.5429	7.67516	48.6622	6.3402
-.042264	.628132	47.5529	7.68632	48.9716	6.3712
-.021132	.628675	46.5710	7.69307	49.1593	6.3900
-.000000	.628854	45.6010	7.69534	49.2227	6.3964

M_∞ = 8.0000000 θ_w = 35° β_c = 39.61°

v	u	β°	T	p	ρ
-.119069	.713577	44.4732	6.37397	37.5019	5.8836
-.099224	.715119	43.6639	6.39612	38.0665	5.9515
-.079379	.716389	42.8490	6.41407	38.5289	6.0069
-.059534	.717378	42.0328	6.42798	38.8903	6.0501
-.039690	.718083	41.2194	6.43794	39.1506	6.0812
-.019845	.718502	40.4124	6.44396	39.3086	6.1000
-.000000	.718641	39.6152	6.44598	39.3619	6.1064

M_∞ = 8.0000000 θ_w = 30° β_c = 33.93°

v	u	β°	T	p	ρ
-.111632	.787249	38.0707	5.23223	28.9015	5.5237
-.093027	.788479	37.3820	5.25203	29.3671	5.5915
-.074421	.789493	36.6877	5.26807	29.7484	5.6469
-.055816	.790284	35.9921	5.28050	30.0466	5.6901
-.037210	.790847	35.2988	5.28939	30.2615	5.7211
-.018605	.791182	34.6111	5.29477	30.3919	5.7399
-.000000	.791293	33.9321	5.29658	30.4360	5.7463

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE I AIR

$\overline{T}_{\infty} = 300°K$, $\gamma_{\infty} = 1.4$, $\overline{\theta}_v = 3101.6°K$

$M_{\infty} = 10.0000000$ $\theta_w = 44°$ $\beta_c = 50.09°$

v	u	β^o	T	p	ρ
-.122585	.551461	56.5326	12.35949	84.1083	6.8051
-.102154	.553569	55.4576	12.39512	85.1912	6.8729
-.081723	.555302	54.3774	12.42402	86.0775	6.9283
-.061292	.556650	53.2970	12.44643	86.7696	6.9714
-.040861	.557610	52.2208	12.46246	87.2674	7.0024
-.020430	.558181	51.1529	12.47214	87.5691	7.0211
-.000000	.558370	50.0973	12.47540	87.6708	7.0274

$M_{\infty} = 10.0000000$ $\theta_w = 40°$ $\beta_c = 45.00°$

v	u	β^o	T	p	ρ
-.115735	.639282	50.2616	10.73492	71.3248	6.6441
-.096446	.640904	49.3855	10.76680	72.2674	6.7120
-.077157	.642239	48.5043	10.79267	73.0391	6.7674
-.057867	.643278	47.6223	10.81273	73.6420	6.8106
-.038578	.644018	46.7432	10.82708	74.0757	6.8417
-.019289	.644459	45.8704	10.83574	74.3386	6.8604
-.000000	.644605	45.0073	10.83866	74.4271	6.8668

$M_{\infty} = 10.0000000$ $\theta_w = 35°$ $\beta_c = 39.11°$

v	u	β^o	T	p	ρ
-.107416	.726440	43.4111	8.87563	56.7851	6.3978
-.089513	.727670	42.6950	8.90328	57.5667	6.4657
-.071610	.728684	41.9741	8.92571	58.2070	6.5212
-.053708	.729473	41.2521	8.94311	58.7072	6.5645
-.035805	.730036	40.5323	8.95556	59.0673	6.5956
-.017902	.730371	39.8175	8.96307	59.2855	6.6144
-.000000	.730482	39.1105	8.96560	59.3591	6.6207

$M_{\infty} = 10.0000000$ $\theta_w = 30°$ $\beta_c = 33.46°$

v	u	β^o	T	p	ρ
-.099226	.797680	37.0907	7.16391	43.5409	6.0778
-.082688	.798638	36.4876	7.18776	44.1742	6.1457
-.066150	.799427	35.8801	7.20711	44.6930	6.2012
-.049613	.800042	35.2715	7.22211	45.0986	6.2445
-.033075	.800480	34.6645	7.23284	45.3906	6.2756
-.016537	.800741	34.0619	7.23932	45.5676	6.2944
-.000000	.800827	33.4661	7.24151	45.6274	6.3008

TABLE I AIR

M_∞ =10.0000000 θ_w = 20° β_c = 22.58°

v	u	β^o	T	p	ρ
-.083914	.904060	25.3029	4.23167	21.5532	5.0933
-.069928	.904667	24.8511	4.24958	21.9317	5.1609
-.055942	.905168	24.3950	4.26407	22.2418	5.2161
-.041957	.905558	23.9377	4.27529	22.4845	5.2591
-.027971	.905836	23.4819	4.28333	22.6595	5.2901
-.013985	.906002	23.0299	4.28819	22.7659	5.3089
-.000000	.906057	22.5840	4.28983	22.8018	5.3153

M_∞ =10.0000000 θ_w = 10° β_c = 12.09°

v	u	β^o	T	p	ρ
-.073930	.968736	14.3641	2.10010	7.0494	3.3567
-.061608	.969183	13.9867	2.11542	7.2405	3.4227
-.049286	.969553	13.6036	2.12772	7.3969	3.4764
-.036965	.969843	13.2192	2.13724	7.5197	3.5184
-.024643	.970048	12.8369	2.14408	7.6088	3.5487
-.012321	.970170	12.4600	2.14824	7.6635	3.5673
-.000000	.970210	12.0913	2.14966	7.6821	3.5736

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE I AIR

$\overline{T}_\infty = 300°K, \quad \gamma_\infty = 1.4, \quad \overline{\theta}_v = 3101.6°K$

$M_\infty = 12.0000000 \quad \theta_w = 44° \quad \beta_c = 49.67°$

v	u	β°	T	p	ρ
-.116330	.564257	55.6491	16.77433	119.0516	7.0972
-.096941	.566112	54.6525	16.82031	120.5169	7.1649
-.077553	.567637	53.6511	16.85763	121.7164	7.2202
-.058165	.568823	52.6494	16.88656	122.6529	7.2633
-.038776	.569668	51.6512	16.90727	123.3265	7.2942
-.019388	.570171	50.6602	16.91976	123.7344	7.3130
-.000000	.570337	49.6799	16.92397	123.8718	7.3193

$M_\infty = 12.0000000 \quad \theta_w = 40° \quad \beta_c = 44.67°$

v	u	β°	T	p	ρ
-.109238	.648661	49.5592	14.49885	101.0134	6.9669
-.091032	.650085	48.7447	14.53949	102.2819	7.0347
-.072825	.651256	47.9256	14.57248	103.3207	7.0901
-.054619	.652167	47.1058	14.59806	104.1321	7.1332
-.036412	.652817	46.2884	14.61637	104.7156	7.1642
-.018206	.653204	45.4765	14.62741	105.0691	7.1830
-.000000	.653332	44.6730	14.63113	105.1881	7.1893

$M_\infty = 12.0000000 \quad \theta_w = 35° \quad \beta_c = 38.81°$

v	u	β°	T	p	ρ
-.100486	.733752	42.7980	11.87580	80.2964	6.7613
-.083738	.734818	42.1352	11.91033	81.3380	6.8292
-.066990	.735695	41.4683	11.93836	82.1913	6.8846
-.050243	.736378	40.8004	11.96010	82.8579	6.9278
-.033495	.736865	40.1343	11.97565	83.3374	6.9589
-.016747	.737155	39.4725	11.98504	83.6279	6.9776
-.000000	.737251	38.8176	11.98820	83.7258	6.9840

$M_\infty = 12.0000000 \quad \theta_w = 30° \quad \beta_c = 33.18°$

v	u	β°	T	p	ρ
-.091754	.803724	36.5127	9.46309	61.3657	6.4847
-.076461	.804536	35.9598	9.49208	62.1983	6.5526
-.061169	.805204	35.4031	9.51560	62.8805	6.6081
-.045877	.805725	34.8454	9.53385	63.4136	6.6514
-.030584	.806096	34.2891	9.54690	63.7973	6.6825
-.015292	.806318	33.7364	9.55478	64.0297	6.7013
-.000000	.806391	33.1895	9.55743	64.1081	6.7076

TABLE I AIR

$M_\infty = 12.0000000$ $\theta_W = 20°$ $\beta_c = 22.30°$

v	u	$\beta°$	T	p	ρ
-.075030	.908347	24.7220	5.37070	29.9344	5.5736
-.062525	.908829	24.3207	5.39079	30.4120	5.6414
-.050020	.909226	23.9161	5.40706	30.8034	5.6968
-.037515	.909536	23.5104	5.41967	31.1095	5.7401
-.025010	.909757	23.1058	5.42870	31.3301	5.7712
-.012505	.909889	22.7043	5.43415	31.4640	5.7900
-.000000	.909932	22.3076	5.43599	31.5092	5.7964

$M_\infty = 12.0000000$ $\theta_W = 10°$ $\beta_c = 11.77°$

v	u	$\beta°$	T	p	ρ
-.062409	.971651	13.6750	2.45329	9.2933	3.7881
-.052008	.971967	13.3592	2.46872	9.5157	3.8545
-.041606	.972228	13.0391	2.48114	9.6978	3.9086
-.031204	.972432	12.7180	2.49076	9.8406	3.9508
-.020803	.972577	12.3984	2.49766	9.9441	3.9813
-.010401	.972663	12.0825	2.50184	10.0073	3.9999
-.000000	.972692	11.7726	2.50326	10.0288	4.0062

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE I AIR

$\bar{T}_\infty = 300°K$, $\gamma_\infty = 1.4$, $\bar{\theta}_v = 3101.6°K$

$M_\infty = 14.0000000$ $\theta_w = 41°$ $\beta_c = 45.67°$

v	u	$\beta°$	T	p	ρ
-.106929	.635361	50.5531	19.65876	141.9712	7.2217
-.089107	.636753	49.7395	19.71156	143.6866	7.2894
-.071286	.637898	48.9216	19.75444	145.0914	7.3447
-.053464	.638789	48.1029	19.78770	146.1883	7.3878
-.035643	.639424	47.2867	19.81150	146.9772	7.4187
-.017821	.639802	46.4758	19.82586	147.4547	7.4374
-.000000	.639927	45.6730	19.83068	147.6155	7.4437

$M_\infty = 14.0000000$ $\theta_w = 40°$ $\beta_c = 44.46°$

v	u	$\beta°$	T	p	ρ
-.105120	.654400	49.1257	18.91789	136.0799	7.1931
-.087600	.655706	48.3490	18.96894	137.7311	7.2608
-.070080	.656781	47.5682	19.01040	139.0835	7.3161
-.052560	.657617	46.7865	19.04256	140.1396	7.3592
-.035040	.658213	46.0071	19.06557	140.8991	7.3902
-.017520	.658569	45.2327	19.07945	141.3589	7.4089
-.000000	.658686	44.4660	19.08412	141.5137	7.4152

$M_\infty = 14.0000000$ $\theta_w = 35°$ $\beta_c = 38.63°$

v	u	$\beta°$	T	p	ρ
-.096047	.738314	42.4120	15.38681	108.0467	7.0220
-.080039	.739280	41.7826	15.42954	109.3924	7.0898
-.064031	.740076	41.1496	15.46424	110.4948	7.1451
-.048023	.740696	40.5156	15.49116	111.3559	7.1883
-.032015	.741138	39.8832	15.51042	111.9752	7.2193
-.016007	.741402	39.2548	15.52204	112.3503	7.2381
-.000000	.741489	38.6325	15.52594	112.4765	7.2444

$M_\infty = 14.0000000$ $\theta_w = 30°$ $\beta_c = 33.01°$

v	u	$\beta°$	T	p	ρ
-.086917	.807545	36.1431	12.14134	82.3886	6.7857
-.072431	.808269	35.6222	12.17649	83.4533	6.8536
-.057945	.808866	35.0978	12.20503	84.3257	6.9090
-.043458	.809331	34.5726	12.22717	85.0073	6.9523
-.028972	.809662	34.0485	12.24301	85.4976	6.9833
-.014486	.809860	33.5277	12.25257	85.7946	7.0021
-.000000	.809925	33.0121	12.25578	85.8946	7.0084

TABLE I AIR

$M_\infty = 14.0000000$ $\theta_W = 20°$ $\beta_c = 22.12°$

v	u	$\beta°$	T	p	ρ
-.069130	.911123	24.3389	6.67419	39.7901	5.9617
-.057608	.911530	23.9708	6.69699	40.3810	6.0297
-.046086	.911866	23.5998	6.71548	40.8653	6.0852
-.034565	.912127	23.2280	6.72982	41.2439	6.1285
-.023043	.912314	22.8570	6.74008	41.5165	6.1596
-.011521	.912425	22.4886	6.74628	41.6819	6.1785
-.000000	.912462	22.1243	6.74836	41.7377	6.1848

$M_\infty = 14.0000000$ $\theta_W = 10°$ $\beta_c = 11.55°$

v	u	$\beta°$	T	p	ρ
-.054738	.973505	13.2182	2.85146	11.9131	4.1779
-.045615	.973746	12.9427	2.86726	12.1707	4.2447
-.036492	.973946	12.6640	2.88001	12.3818	4.2992
-.027369	.974102	12.3843	2.88988	12.5472	4.3417
-.018246	.974213	12.1058	2.89696	12.6668	4.3724
-.009123	.974279	11.8302	2.90125	12.7397	4.3911
-.000000	.974300	11.5592	2.90270	12.7645	4.3974

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE I AIR

$\bar{T}_\infty = 300°K$, $\gamma_\infty = 1.4$, $\bar{\theta}_v = 3101.6°K$

$M_\infty = 16.0000000$ $\theta_w = 35°$ $\beta_c = 38.50°$

v	u	β^o	T	p	ρ
-.093048	.741343	42.1539	19.41664	140.0456	7.2126
-.077540	.742247	41.5469	19.46888	141.7404	7.2803
-.062032	.742990	40.9365	19.51132	143.1288	7.3356
-.046524	.743570	40.3251	19.54425	144.2132	7.3788
-.031016	.743982	39.7152	19.56780	144.9931	7.4097
-.015508	.744229	39.1090	19.58201	145.4651	7.4285
-.000000	.744310	38.5085	19.58679	145.6240	7.4348

$M_\infty = 16.0000000$ $\theta_w = 30°$ $\beta_c = 32.89°$

v	u	β^o	T	p	ρ
-.083617	.810112	35.8930	15.20658	106.6185	7.0113
-.069681	.810780	35.3936	15.24889	107.9487	7.0791
-.055745	.811330	34.8911	15.28326	109.0387	7.1345
-.041808	.811759	34.3877	15.30992	109.8902	7.1777
-.027872	.812064	33.8855	15.32900	110.5026	7.2087
-.013936	.812246	33.3863	15.34051	110.8734	7.2274
-.000000	.812307	32.8918	15.34437	110.9983	7.2338

$M_\infty = 16.0000000$ $\theta_w = 20°$ $\beta_c = 21.99°$

v	u	β^o	T	p	ρ
-.064996	.913034	24.0718	8.14680	51.1246	6.2754
-.054163	.913393	23.7268	8.17283	51.8432	6.3433
-.043330	.913689	23.3792	8.19395	52.4322	6.3988
-.032498	.913919	23.0308	8.21033	52.8925	6.4421
-.021665	.914084	22.6832	8.22205	53.2239	6.4733
-.010832	.914181	22.3378	8.22913	53.4248	6.4921
-.000000	.914214	21.9961	8.23151	53.4925	6.4985

$M_\infty = 16.0000000$ $\theta_w = 10°$ $\beta_c = 11.40°$

v	u	β^o	T	p	ρ
-.049276	.974785	12.8939	3.29170	14.9050	4.5280
-.041064	.974979	12.6469	3.30807	15.2013	4.5952
-.032851	.975140	12.3972	3.32130	15.4440	4.6500
-.024638	.975266	12.1468	3.33154	15.6341	4.6927
-.016425	.975355	11.8972	3.33888	15.7714	4.7235
-.008212	.975408	11.6500	3.34332	15.8551	4.7423
-.000000	.975426	11.4065	3.34482	15.8834	4.7486

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE I AIR

$\bar{T}_\infty = 300°K$, $\gamma_\infty = 1.4$, $\bar{\theta}_v = 3101.6°K$

$M_\infty = 18.0000000$ $\theta_w = 30°$ $\beta_c = 32.80°$

v	u	$\beta°$	T	p	ρ
-.081272	.811918	35.7162	18.66392	134.0608	7.1828
-.067726	.812547	35.2320	18.71438	135.6906	7.2506
-.054181	.813066	34.7449	18.75538	137.0259	7.3059
-.040636	.813469	34.2570	18.78719	138.0690	7.3491
-.027090	.813757	33.7701	18.80995	138.8191	7.3800
-.013545	.813929	33.2861	18.82368	139.2732	7.3988
-.000000	.813986	32.8066	18.82829	139.4260	7.4051

$M_\infty = 18.0000000$ $\theta_w = 20°$ $\beta_c = 21.90°$

v	u	$\beta°$	T	p	ρ
-.061994	.914405	23.8785	9.79312	63.9449	6.5295
-.051662	.914730	23.5501	9.82286	64.8063	6.5974
-.041329	.914999	23.2194	9.84701	65.5122	6.6530
-.030997	.915208	22.8880	9.86574	66.0639	6.6962
-.020664	.915357	22.5572	9.87914	66.4609	6.7274
-.010332	.915446	22.2285	9.88723	66.7014	6.7462
-.000000	.915475	21.9031	9.88995	66.7825	6.7525

$M_\infty = 18.0000000$ $\theta_w = 10°$ $\beta_c = 11.29°$

v	u	$\beta°$	T	p	ρ
-.045234	.975709	12.6543	3.77341	18.2738	4.8427
-.037695	.975872	12.4283	3.79053	18.6122	4.9102
-.030156	.976008	12.2000	3.80437	18.8896	4.9652
-.022617	.976113	11.9710	3.81510	19.1068	5.0082
-.015078	.976188	11.7427	3.82278	19.2635	5.0391
-.007539	.976233	11.5163	3.82742	19.3588	5.0579
-.000000	.976247	11.2932	3.82899	19.3910	5.0642

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE I AIR

$\bar{T}_\infty$ = 300°K, γ_∞ = 1.4, $\bar{\theta}_v$ = 3101.6°K

M_∞ = 20.0000000 θ_w = 20° β_c = 21.83°

v	u	β°	T	p	ρ
-.059748	.915421	23.7343	11.61648	78.2546	6.7365
-.049790	.915723	23.4183	11.65041	79.2740	6.8043
-.039832	.915972	23.1001	11.67797	80.1094	6.8598
-.029874	.916166	22.7813	11.69935	80.7622	6.9031
-.019916	.916304	22.4631	11.71465	81.2318	6.9342
-.009958	.916387	22.1468	11.72388	81.5163	6.9530
-.000000	.916414	21.8336	11.72698	81.6121	6.9593

M_∞ = 20.0000000 θ_w = 10° β_c = 11.20°

v	u	β°	T	p	ρ
-.042132	.976406	12.4707	4.29597	22.0183	5.1253
-.035110	.976547	12.2607	4.31399	22.4024	5.1929
-.028088	.976664	12.0486	4.32858	22.7173	5.2482
-.021066	.976755	11.8360	4.33989	22.9636	5.2912
-.014044	.976820	11.6239	4.34798	23.1413	5.3223
-.007022	.976859	11.4135	4.35288	23.2493	5.3411
-.000000	.976872	11.2059	4.35453	23.2858	5.3474

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE II NITROGEN

$\bar{T}_\infty = 300°K$, $\gamma_\infty = 1.4$, $\bar{\theta}_v = 3336°K$

$M_\infty = 8.0000000$ $\theta_w = 44°$ $\beta_c = 50.97°$

v	u	β°	T	p	ρ
-.134510	.524049	58.3956	8.80121	55.7289	6.3319
-.112092	.526722	57.1534	8.82905	56.5046	6.3998
-.089673	.528919	55.9053	8.85160	57.1391	6.4552
-.067255	.530628	54.6576	8.86907	57.6345	6.4983
-.044836	.531843	53.4159	8.88157	57.9912	6.5293
-.022418	.532566	52.1851	8.88913	58.2075	6.5481
-.000000	.532804	50.9702	8.89167	58.2805	6.5545

$M_\infty = 8.0000000$ $\theta_w = 40°$ $\beta_c = 45.66°$

v	u	β°	T	p	ρ
-.127914	.620483	51.6485	7.68508	47.1159	6.1308
-.106595	.622527	50.6497	7.71045	47.7951	6.1987
-.085276	.624209	49.6449	7.73100	48.3511	6.2541
-.063957	.625519	48.6394	7.74693	48.7855	6.2973
-.042638	.626451	47.6378	7.75834	49.0982	6.3284
-.021319	.627005	46.6443	7.76522	49.2879	6.3472
-.000000	.627188	45.6651	7.76754	49.3519	6.3536

$M_\infty = 8.0000000$ $\theta_w = 35°$ $\beta_c = 39.66°$

v	u	β°	T	p	ρ
-.120170	.712323	44.5757	6.43432	37.5795	5.8404
-.100142	.713896	43.7574	6.45700	38.1504	5.9083
-.080113	.715192	42.9333	6.47537	38.6178	5.9638
-.060085	.716202	42.1060	6.48961	38.9832	6.0070
-.040056	.716920	41.2855	6.49980	39.2464	6.0380
-.020028	.717349	40.4696	6.50596	39.4061	6.0569
-.000000	.717490	39.6637	6.50803	39.4600	6.0632

$M_\infty = 8.0000000$ $\theta_w = 30°$ $\beta_c = 33.97°$

v	u	β°	T	p	ρ
-.112680	.786344	38.1547	5.28208	28.9595	5.4826
-.093900	.787599	37.4506	5.30239	29.4303	5.5503
-.075120	.788634	36.7568	5.31883	29.8158	5.6057
-.056340	.789441	36.0537	5.33158	30.1173	5.6488
-.037560	.790015	35.3530	5.34070	30.3346	5.6798
-.018780	.790357	34.6580	5.34622	30.4666	5.6987
-.000000	.790470	33.9718	5.34806	30.5111	5.7050

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE II NITROGEN

$\overline{T}_\infty$ = 300°K, γ_∞ = 1.4, $\overline{\theta}_v$ = 3336°K

M_∞ = 10.0000000 θ_w = 44° β_c = 50.15°

v	u	β°	T	p	ρ
-.123436	.549646	56.6571	12.45089	84.2682	6.7680
-.102863	.551790	55.5710	12.48708	85.3601	6.8358
-.082291	.553554	54.4797	12.51643	86.2538	6.8912
-.061718	.554925	53.3882	12.53918	86.9516	6.9343
-.041145	.555901	52.3010	12.55546	87.4537	6.9653
-.020572	.556483	51.2223	12.56529	87.7579	6.9841
-.000000	.556675	50.1560	12.56859	87.8604	6.9904

M_∞ = 10.0000000 θ_w = 40° β_c = 45.05°

v	u	β°	T	p	ρ
-.116592	.638014	50.3561	10.81734	71.4423	6.6044
-.097160	.639663	49.4716	10.84977	72.3930	6.6723
-.077728	.641021	48.5821	10.87607	73.1715	6.7277
-.058296	.642078	47.6917	10.89647	73.7796	6.7709
-.038864	.642830	46.8043	10.91106	74.2171	6.8020
-.019432	.643278	45.9233	10.91987	74.4823	6.8208
-.000000	.643427	45.0522	10.92284	74.5717	6.8271

M_∞ = 10.0000000 θ_w = 35° β_c = 39.14°

v	u	β°	T	p	ρ
-.108288	.725502	43.4892	8.94925	56.8767	6.3554
-.090240	.726755	42.7662	8.97744	57.6658	6.4234
-.072192	.727786	42.0305	9.00030	58.3121	6.4789
-.054144	.728590	41.3096	9.01803	58.8171	6.5221
-.036096	.729162	40.5829	9.03072	59.1806	6.5532
-.018048	.729503	39.8614	9.03838	59.4010	6.5720
-.000000	.729616	39.1478	9.04095	59.4752	6.5784

M_∞ = 10.0000000 θ_w = 30° β_c = 33.49°

v	u	β°	T	p	ρ
-.100103	.796959	37.1592	7.22803	43.6144	6.0340
-.083419	.797935	36.5501	7.25242	44.2543	6.1020
-.066735	.798739	35.9366	7.27219	44.7785	6.1575
-.050051	.799365	35.3219	7.28751	45.1882	6.2007
-.033367	.799811	34.7089	7.29848	45.4833	6.2318
-.016683	.800077	34.1004	7.30511	45.6622	6.2507
-.000000	.800165	33.4987	7.30734	45.7226	6.2570

TABLE II NITROGEN

M_∞ = 10.0000000 θ_w = 20° β_c = 22.60°

v	u	β°	T	p	ρ
-.084672	.903688	25.3527	4.26986	21.5927	5.0570
-.070560	.904306	24.8965	4.28825	21.9752	5.1245
-.056448	.904816	24.4360	4.30313	22.2886	5.1796
-.042336	.905214	23.9743	4.31466	22.5339	5.2226
-.028224	.905498	23.5140	4.32291	22.7108	5.2535
-.014112	.905667	23.0577	4.32790	22.8183	5.2723
-.000000	.905722	22.6075	4.32959	22.8547	5.2787

M_∞ = 10.0000000 θ_w = 10° β_c = 12.09°

v	u	β°	T	p	ρ
-.074151	.968682	14.3773	2.10686	7.0536	3.3479
-.061792	.969131	13.9967	2.12241	7.2452	3.4136
-.049434	.969504	13.6142	2.13491	7.4021	3.4671
-.037075	.969795	13.2285	2.14458	7.5252	3.5089
-.024717	.970002	12.8450	2.15153	7.6146	3.5392
-.012358	.970125	12.4669	2.15575	7.6695	3.5576
-.000000	.970165	12.0970	2.15719	7.6881	3.5639

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE II NITROGEN

$\bar{T}_\infty = 300°K$, $\gamma_\infty = 1.4$, $\bar{\theta}_v = 3336°K$

$M_\infty = 12.0000000$ $\theta_w = 44°$ $\beta_c = 49.72°$

v	u	β°	T	p	ρ
-.116974	.562981	55.7377	16.87248	119.2137	7.0655
-.097478	.564861	54.7332	16.91901	120.6886	7.1333
-.077982	.566406	53.7239	16.95677	121.8960	7.1886
-.058487	.567608	52.7144	16.98605	122.8387	7.2317
-.038991	.568464	51.7084	17.00700	123.5166	7.2626
-.019495	.568974	50.7097	17.01965	123.9272	7.2814
-.000000	.569143	49.7218	17.02390	124.0656	7.2877

$M_\infty = 12.0000000$ $\theta_w = 40°$ $\beta_c = 44.70°$

v	u	β°	T	p	ρ
-.109901	.647722	49.6299	14.58957	101.1396	6.9323
-.091584	.649165	48.8091	14.63075	102.4171	7.0001
-.073267	.650352	47.9839	14.66418	103.4633	7.0555
-.054950	.651276	47.1578	14.69010	104.2804	7.0986
-.036634	.651934	46.3342	14.70865	104.8682	7.1296
-.018317	.652327	45.5162	14.71985	105.2241	7.1484
-.000000	.652457	44.7067	14.72361	105.3440	7.1547

$M_\infty = 12.0000000$ $\theta_w = 35°$ $\beta_c = 38.84°$

v	u	β°	T	p	ρ
-.101175	.733035	42.8584	11.95884	80.3982	6.7229
-.084313	.734116	42.1904	11.99391	81.4481	6.7907
-.067450	.735007	41.5182	12.02237	82.3081	6.8462
-.050587	.735700	40.8450	12.04445	82.9800	6.8894
-.033725	.736194	40.1736	12.06024	83.4634	6.9205
-.016862	.736489	39.5066	12.06978	83.7563	6.9393
-.000000	.736586	38.8465	12.07298	83.8549	6.9456

$M_\infty = 12.0000000$ $\theta_w = 30°$ $\beta_c = 33.21°$

v	u	β°	T	p	ρ
-.092470	.803152	36.5677	9.53780	61.4506	6.4428
-.077058	.803977	36.0100	9.56732	62.2908	6.5107
-.061646	.804657	35.4465	9.59127	62.9792	6.5663
-.046235	.805186	34.8860	9.60985	63.5171	6.6095
-.030823	.805564	34.3249	9.62314	63.9043	6.6406
-.015411	.805789	33.7675	9.63117	64.1389	6.6595
-.000000	.805863	33.2159	9.63387	64.2179	6.6658

TABLE II NITROGEN

$M_\infty = 12.0000000$ $\theta_w = 20°$ $\beta_c = 22.32°$

v	u	$\beta°$	T	p	ρ
-.075730	.908015	24.7675	5.42080	29.9862	5.5316
-.063108	.908506	24.3623	5.44139	30.4691	5.5995
-.050486	.908911	23.9536	5.45807	30.8647	5.6548
-.037865	.909227	23.5439	5.47100	31.1742	5.6980
-.025243	.909452	23.1353	5.48026	31.3972	5.7291
-.012621	.909586	22.7298	5.48585	31.5326	5.7479
-.000000	.909630	22.3293	5.48774	31.5783	5.7543

$M_\infty = 12.0000000$ $\theta_w = 10°$ $\beta_c = 11.78°$

v	u	$\beta°$	T	p	ρ
-.062727	.971573	13.6940	2.46547	9.3047	3.7740
-.052272	.971892	13.3763	2.48122	9.5284	3.8402
-.041818	.972156	13.0545	2.49391	9.7116	3.8941
-.031363	.972363	12.7316	2.50373	9.8553	3.9362
-.020909	.972509	12.4102	2.51078	9.9594	3.9666
-.010454	.972596	12.0927	2.51505	10.0230	3.9852
-.000000	.972625	11.7812	2.51650	10.0446	3.9915

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE II NITROGEN

$\bar{T}_\infty$ = 300°K, γ_∞ = 1.4, $\bar{\theta}_v$ = 3336°K

M_∞ = 14.0000000 θ_w = 41° β_c = 45.70°

v	u	β°	T	p	ρ
-.107444	.634600	50.6096	19.75656	142.1089	7.1930
-.089536	.636007	49.7910	19.80991	143.8339	7.2607
-.071629	.637164	48.9681	19.85323	145.2465	7.3160
-.053722	.638065	48.1445	19.88683	146.3497	7.3591
-.035814	.638707	47.3233	19.91087	147.1429	7.3900
-.017907	.639090	46.5076	19.92538	147.6232	7.4088
-.000000	.639216	45.7000	19.93025	147.7849	7.4151

M_∞ = 14.0000000 θ_w = 40° β_c = 44.49°

v	u	β°	T	p	ρ
-.105640	.653683	49.1800	19.01428	136.2113	7.1636
-.088033	.655004	48.3986	19.06588	137.8721	7.2313
-.070427	.656090	47.6130	19.10777	139.2323	7.2866
-.052820	.656936	46.8266	19.14027	140.2945	7.3298
-.035213	.657538	46.0424	19.16353	141.0583	7.3607
-.017606	.657898	45.2633	19.17756	141.5208	7.3795
-.000000	.658016	44.4919	19.18227	141.6765	7.3858

M_∞ = 14.0000000 θ_w = 35° β_c = 38.65°

v	u	β°	T	p	ρ
-.096600	.737750	42.4598	15.47668	108.1565	6.9883
-.080500	.738729	41.8264	15.51995	109.5112	7.0561
-.064400	.739534	41.1891	15.55509	110.6210	7.1115
-.048300	.740162	40.5509	15.58235	111.4879	7.1547
-.032200	.740609	39.9144	15.60185	112.1114	7.1857
-.016100	.740876	39.2818	15.61362	112.4889	7.2045
-.000000	.740964	38.6555	15.61757	112.6160	7.2108

M_∞ = 14.0000000 θ_w = 30° β_c = 33.03°

v	u	β°	T	p	ρ
-.087502	.807087	36.1876	12.22386	82.4819	6.7476
-.072918	.807821	35.6628	12.25955	83.5549	6.8155
-.058334	.808426	35.1346	12.28852	84.4341	6.8709
-.043751	.808898	34.6054	12.31099	85.1210	6.9142
-.029167	.809234	34.0775	12.32707	85.6151	6.9452
-.014583	.809434	33.5529	12.33677	85.9144	6.9640
-.000000	.809500	33.0335	12.34004	86.0152	6.9704

TABLE II NITROGEN

$M_\infty = 14.0000000$ $\theta_w = 20°$ $\beta_c = 22.14°$

v	u	β°	T	p	ρ
-.069750	.910834	24.3790	6.73422	39.8521	5.9178
-.058125	.911249	24.0075	6.75754	40.4492	5.9857
-.046500	.911590	23.6330	6.77646	40.9385	6.0412
-.034875	.911857	23.2576	6.79112	41.3211	6.0845
-.023250	.912047	22.8831	6.80161	41.5966	6.1157
-.011625	.912160	22.5113	6.80795	41.7637	6.1345
.000000	.912198	22.1436	6.81009	41.8201	6.1409

$M_\infty = 14.0000000$ $\theta_w = 10°$ $\beta_c = 11.56°$

v	u	β°	T	p	ρ
-.055077	.973426	13.2384	2.86951	11.9285	4.1570
-.045898	.973670	12.9611	2.88569	12.1879	4.2235
-.036718	.973872	12.6804	2.89874	12.4005	4.2778
-.027538	.974030	12.3990	2.90885	12.5670	4.3202
-.018359	.974142	12.1186	2.91610	12.6875	4.3508
-.009179	.974209	11.8412	2.92049	12.7610	4.3694
-.000000	.974231	11.5684	2.92197	12.7859	4.3757

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE II NITROGEN

$\bar{T}_\infty = 300°K$, $\gamma_\infty = 1.4$, $\bar{\theta}_v = 3336°K$

$M_\infty = 16.0000000$ $\theta_w = 35°$ $\beta_c = 38.52°$

v	u	β°	T	p	ρ
-.093495	.740895	42.1922	19.51130	140.1599	7.1835
-.077912	.741808	41.5819	19.56408	141.8640	7.2512
-.062330	.742559	40.9681	19.60696	143.2601	7.3065
-.046747	.743144	40.3534	19.64022	144.3505	7.3497
-.031165	.743561	39.7401	19.66401	145.1347	7.3807
-.015582	.743810	39.1306	19.67837	145.6094	7.3994
-.000000	.743892	38.5269	19.68320	145.7691	7.4057

$M_\infty = 16.0000000$ $\theta_w = 30°$ $\beta_c = 32.90°$

v	u	β°	T	p	ρ
-.084098	.809740	35.9294	15.29490	106.7180	6.9773
-.070082	.810416	35.4268	15.33775	108.0570	7.0451
-.056065	.810973	34.9212	15.37255	109.1542	7.1005
-.042049	.811406	34.4146	15.39955	110.0113	7.1438
-.028032	.811716	33.9092	15.41887	110.6278	7.1748
-.014016	.811900	33.4068	15.43052	111.0011	7.1936
-.000000	.811961	32.9093	15.43444	111.1268	7.1999

$M_\infty = 16.0000000$ $\theta_w = 20°$ $\beta_c = 22.01°$

v	u	β°	T	p	ρ
-.065539	.912785	24.1068	8.21499	51.1953	6.2319
-.054615	.913150	23.7588	8.24154	51.9209	6.2999
-.043692	.913450	23.4081	8.26309	52.5156	6.3554
-.032769	.913685	23.0567	8.27980	52.9804	6.3987
-.021846	.913852	22.7060	8.29175	53.3150	6.4298
-.010923	.913952	22.3576	8.29897	53.5178	6.4487
-.000000	.913985	22.0130	8.30140	53.5862	6.4550

$M_\infty = 16.0000000$ $\theta_w = 10°$ $\beta_c = 11.41°$

v	u	β°	T	p	ρ
-.049658	.974696	12.9165	3.31684	14.9293	4.5010
-.041381	.974894	12.6675	3.33364	15.2283	4.5680
-.033105	.975058	12.4158	3.34721	15.4732	4.6227
-.024829	.975185	12.1633	3.35772	15.6651	4.6653
-.016552	.975276	11.9117	3.36526	15.8037	4.6961
-.008276	.975330	11.6625	3.36982	15.8881	4.7148
-.000000	.975348	11.4171	3.37136	15.9167	4.7211

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE II NITROGEN

$\bar{T}_\infty = 300°K$, $\gamma_\infty = 1.4$, $\bar{\theta}_v = 3336°K$

$M_\infty = 18.0000000$ $\theta_w = 30°$ $\beta_c = 32.82°$

v	u	$\beta°$	T	p	ρ
-.081672	.811611	35.7462	18.75663	134.1650	7.1529
-.068060	.812247	35.2595	18.80764	135.8039	7.2206
-.054448	.812771	34.7698	18.84907	137.1468	7.2760
-.040836	.813179	34.2792	18.88122	138.1958	7.3192
-.027224	.813469	33.7898	18.90422	138.9502	7.3502
-.013612	.813643	33.3031	18.91809	139.4068	7.3689
-.000000	.813700	32.8211	18.92275	139.5605	7.3752

$M_\infty = 18.0000000$ $\theta_w = 20°$ $\beta_c = 21.91°$

v	u	$\beta°$	T	p	ρ
-.062467	.914190	23.9089	9.86789	64.0226	6.4879
-.052055	.914521	23.5779	9.89817	64.8915	6.5559
-.041644	.914793	23.2445	9.92274	65.6036	6.6114
-.031233	.915006	22.9104	9.94181	66.1602	6.6547
-.020822	.915157	22.5770	9.95545	66.5607	6.6858
-.010411	.915248	22.2457	9.96368	66.8033	6.7046
-.000000	.915277	21.9178	9.96645	66.8851	6.7110

$M_\infty = 18.0000000$ $\theta_w = 10°$ $\beta_c = 11.30°$

v	u	$\beta°$	T	p	ρ
-.045622	.975621	12.6773	3.80540	18.3049	4.8102
-.038018	.975787	12.4492	3.82298	18.6468	4.8775
-.030414	.975925	12.2168	3.83720	18.9270	4.9325
-.022811	.976032	11.9878	3.84821	19.1463	4.9753
-.015207	.976109	11.7574	3.85610	19.3046	5.0062
-.007603	.976154	11.5291	3.86087	19.4009	5.0250
-.000000	.976169	11.3040	3.86248	19.4335	5.0313

VIBRATIONAL EQUILIBRIUM CONICAL FLOW

TABLE II NITROGEN

$\bar{T}_\infty$ = 300°K, γ_∞ = 1.4, $\bar{\theta}_v$ = 3336°K

M_∞ = 20.0000000 θ_w = 20° β_c = 21.84°

v	u	β°	T	p	ρ
-.060159	.915236	23.7606	11.69659	78.3377	6.6974
-.050132	.915542	23.4424	11.73106	79.3652	6.7653
-.040106	.915794	23.1219	11.75905	80.2072	6.8208
-.030079	.915991	22.8008	11.78076	80.8652	6.8641
-.020053	.916131	22.4803	11.79630	81.3385	6.8952
-.010026	.916215	22.1618	11.80568	81.6253	6.9140
-.000000	.916243	21.8463	11.80883	81.7218	6.9204

M_∞ = 20.0000000 θ_w = 10° β_c = 11.21°

v	u	β°	T	p	ρ
-.042513	.976321	12.4933	4.33458	22.0561	5.0884
-.035427	.976465	12.2813	4.35309	22.4443	5.1559
-.028342	.976584	12.0672	4.36807	22.7625	5.2111
-.021256	.976677	11.8525	4.37968	23.0115	5.2541
-.014171	.976743	11.6385	4.38799	23.1911	5.2851
-.007085	.976782	11.4261	4.39302	23.3002	5.3039
-.000000	.976795	11.2166	4.39471	23.3371	5.3102

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CONICAL FLOW PARAMETERS FOR AIR AND NITROGEN IN VIBRATIONAL EQUILIBRIUM

Paul D. Kelly

Gas flow - Analysis
Supersonic flow - Tables

BRL Report 1164 March 1962

DA Proj 503-03-001, OMSC 5010.11.814
UNCLASSIFIED Report

The Taylor-Maccoll equation for supersonic flow about cones has been integrated numerically for air and nitrogen in instantaneous vibrational equilibrium (chemical reactions are assumed to be frozen). Free stream Mach numbers from 8 to 20 were used for 300° K free stream temperature.

The values of the flow quantities (i.e. velocity components, polar angle, temperature, pressure and density) are given through the shock layer for different values of M_∞ and flow deflection angle at the shock.

It was found that by non-dimensionalizing some of the flow quantities (temperature, pressure and density) with respect to the changes in their values across the shock layer and by plotting them as functions of the non-dimensional shock layer thickness, that the points for different values of M_∞ and cone angle lie along the same curves. This gives an approximate method of obtaining other solutions.

The results presented here are shown to lie between those of Kopal (translation and rotational degrees of freedom only) and Romig (dissociation and ionization included) as is expected.

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